CANADIAN JOURNAL OF RESEARCH

VOLUME 22 SEPTEMBER, 1944 NUMBER 5

— SECTION A —

PHYSICAL SCIENCES

Contents

Page

A Voltage Amplifier Using a Pre-saturation Diode as Load—
A. M. I. A. W. Durnford - - - - - - - - - - 67

NATIONAL RESEARCH COUNCIL
OTTAWA, CANADA

CANADIAN JOURNAL OF RESEARCH

The *Canadian Journal of Research* is issued in six sections, as follows:

A. Physical Sciences
B. Chemical Sciences
C. Botanical Sciences
D. Zoological Sciences
E. Medical Sciences
F. Technology

For the present, each of these sections is to be issued six times annually, under separate cover, with separate pagination.

The *Canadian Journal of Research* is published by the National Research Council of Canada under authority of the Chairman of the Committee of the Privy Council on Scientific and Industrial Research. The *Canadian Journal of Research* is edited by a joint Editorial Board consisting of members of the National Research Council of Canada and the Royal Society of Canada.

EDITORIAL BOARD

Representing National Research Council	*Representing* Royal Society of Canada	
Dr. R. Newton (*Chairman*) President, University of Alberta, Edmonton.	Dr. C. C. Coffin, Professor of Chemistry, Dalhousie University, Halifax.	Section III
Dr. J. B. Collip, Director, Research Institute of Endocrinology, McGill University, Montreal.	Prof. J. K. Robertson, Department of Physics, Queen's University, Kingston.	
Dr. J. A. Gray, Professor of Physics, Queen's University, Kingston.	Prof. J. R. Dymond, Royal Ontario Museum of Zoology, Toronto.	Section V
Dr. O. Maass, Professor of Physical Chemistry, McGill University, Montreal.	Dr. C. L. Huskins, Professor of Genetics, McGill University, Montreal.	

Ex officio, Dr. W. H. Cook, Editor-in-Chief,
Director, Division of Applied Biology,
National Research Laboratories, Ottawa.

Editorial Committee

Editor-in-Chief, Dr. W. H. Cook
Editor Section A, Prof. J. K. Robertson
Editor Section B, Dr. C. C. Coffin
Editor Section C, Dr. C. L. Huskins
Editor Section D, Prof. J. R. Dymond
Editor Section E, Dr. J. B. Collip
Editor Section F, Dr. E. L. Harrington

Manuscripts should be addressed:

Editor-in-Chief,
Canadian Journal of Research,
National Research Council, Ottawa, Canada.

Canadian Journal of Research

Issued by THE NATIONAL RESEARCH COUNCIL OF CANADA

VOL. 22, SEC. A. SEPTEMBER, 1944 NUMBER 5

A VOLTAGE AMPLIFIER USING A PRE-SATURATION DIODE AS LOAD[1]

BY A. M. I. A. W. DURNFORD[2]

Abstract

Pre-saturation characteristics for various types of diodes indicate that for constant plate voltage, the product of plate current and plate resistance is constant for each diode. ($i_d r_{pd} = K$). For different diodes, the value of K varies from 200 to 700 v. for a plate voltage of 125 v. Tubes with thoriated tungsten cathodes have the highest K values, with K proportional to plate voltage which renders the logarithmic characteristics linear and parallel. The pre-saturation diode when used as a load provides a high resistance that does not require an exceedingly large supply voltage. If the quiescent plate voltage, E_{bo}, is kept constant, the effective load lines converge at a common point, the voltage of which represents a virtual supply voltage equal to $E_{bo} + K$. Voltage gain and maximum distortionless output are both greater than when a fixed resistance is used as load. Variation of the filament current of the diode, or of a self-bias resistor, provides a distortionless gain control. The gain is almost constant for frequencies less than 300 c.p.s. but for higher frequencies drops more rapidly.

A. Introduction

1. *Voltage Gain*

The voltage gain, G, for an amplifier with load Z_L is given by the expression $G = \mu Z_L/(r_p + Z_L)$, where $Z_L = R_L + jX_L$. Thus for a pure resistance load, $G = \mu/(1 + r_p/R_L)$. Accordingly, if $R_L \gg r_p$, $G \doteq \mu$, the amplification factor. However, the above condition is not generally imposed since the use of a very large resistance load, R_L, requires an exceedingly large supply voltage, E_{bb}.

For high mu triodes, the plate resistance, r_p, is about 50,000 ohms; consequently, in practice R_L can be made greater than r_p to yield a gain greater than $\mu/2$. However, for pentodes, r_p is generally greater than a megohm so that even for $R_L = r_p$, the minimum voltage drop across the load would equal 1000 volts, assuming a quiescent plate current of 1.0 ma. This means that although pentodes have a very high μ, a correspondingly high gain is not obtainable with moderate voltages.

Herd (4), Mills (5), and Rudolph (7) have investigated the use of a saturated diode as an anode resistance, chiefly in connection with triodes. With a view to obtaining maximum gain using a pentode as the control tube, the author has investigated the saturation characteristics of various diodes for moderate voltages.

[1] *Manuscript received in original form August 5, 1943, and as revised, April 12, 1944. Contribution from the Department of Physics, University of Western Ontario, London, Ont.*

[2] *Assistant Professor of Physics.*

The results indicate that for a plate voltage less than 150, a high degree of saturation is not obtainable except by operating the cathode at a temperature lower than its rated value. This procedure decreases the plate current delivered by the diode. Accordingly, very large values of plate resistance for the diode, r_{pd}, are associated with very small values of plate current. However, in order to have the operation of the pentode reasonably free from distortion, it is essential that the plate current be maintained above a certain minimum value. This imposes a maximum value on r_{pd}.

If then one excludes the use of high voltages, it can hardly be said that the diode is being operated at saturation. Thus the term pre-saturation is employed herein to designate the condition resulting in a large but finite plate resistance for the diode. Since the saturated diode furnishes an ideal for performance, a treatment of this is given as an introduction to the use of the pre-saturation diode.

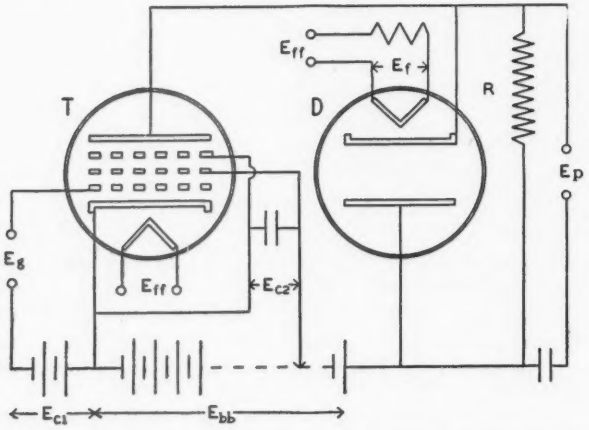

FIG. 1. *Circuit diagram of diode used as an anode resistance; T, control tube (triode or pentode); D, diode; R, fixed resistance.*

2. *The Saturated Diode as an Anode Resistance*

Assume e_b = voltage between plate and cathode of T, Fig. 1.
e_d = voltage between plate and cathode of D, Fig. 1.
i_b = plate current through T
i_d = plate current through D
i_R = current through R, Fig. 1.

Then we have the following equations:

$$e_b + e_d = E_{bb} \tag{1}$$
$$e_d = i_R R \tag{2}$$
$$i_b = i_d + i_R \tag{3}$$

whence,

$$e_d = (i_b - i_d)R \tag{2a}$$

and

$$e_b + (i_b - i_d)R = E_{bb} \tag{1a}$$

or

$$e_b + i_bR = E_{bb} + i_dR \tag{4}$$

If then D is operated at saturation, i_d is constant and the above may be written,

$$e_b + i_bR = E'_{bb} \tag{5}$$

Equation (5) represents the load line for the tube T with load resistance R and battery voltage E'_{bb}. Thus it would appear that the operation of T with the saturated diode is the same as using a fixed resistance R with a supply voltage equal to $E_{bb} + i_dR$. Moreover, as R is increased the load line becomes more nearly horizontal; hence for large values of R the circuit would function as a constant current voltage amplifier, with the gain equal to the amplification factor of T.

B. Pre-Saturation Characteristics

In practice, the diode must be considered as having a finite plate resistance, r_{pd}, and it is desirable to know the type of diode that yields the largest r_{pd} for a given plate current and plate voltage, i.e., for a given operating point. Accordingly, characteristics for different diodes were obtained by keeping the filament (or heater) current constant and varying the plate voltage to yield corresponding values of plate current. Several characteristics for each tube were obtained by using different filament (or heater) currents. Fig. 2 illustrates a typical set of characteristics.

Plate resistance values, $\Delta e_d/\Delta i_d$, were computed for a number of operating points. For constant plate voltage, r_{pd} increases with decrease in plate current, i.e., with decrease in cathode temperature. However, it was found that a simple relation exists between i_d and r_{pd}; namely, for constant plate voltage the product i_dr_{pd} is constant. This is indicated in Fig. 2 and supported by Tables I and II. Table II includes the range of values of plate current for which plate resistances were computed and also the percentage deviation of the mean value of i_dr_{pd}. In the case of triodes and pentodes all grids were connected to the plate.

With i_dr_{pd} = a constant, K, for constant plate voltage, the constant K can be employed to determine the value of r_{pd} for any value of i_d. Also the constant K provides a magnitude for the comparison of diodes when used as anode resistances.

It can be seen, from Table II, that the tubes with thoriated tungsten cathodes not only have the highest K values but also have K proportional to e_d. Thus $i_dr_{pd} = me_d$, with the constant m independent of both i_d and e_d. However, $r_{pd} = \Delta e_d/\Delta i_d$ for constant cathode temperature. Accordingly, dropping the subscript and using differentials, $i\dfrac{de}{di} = me$, which yields

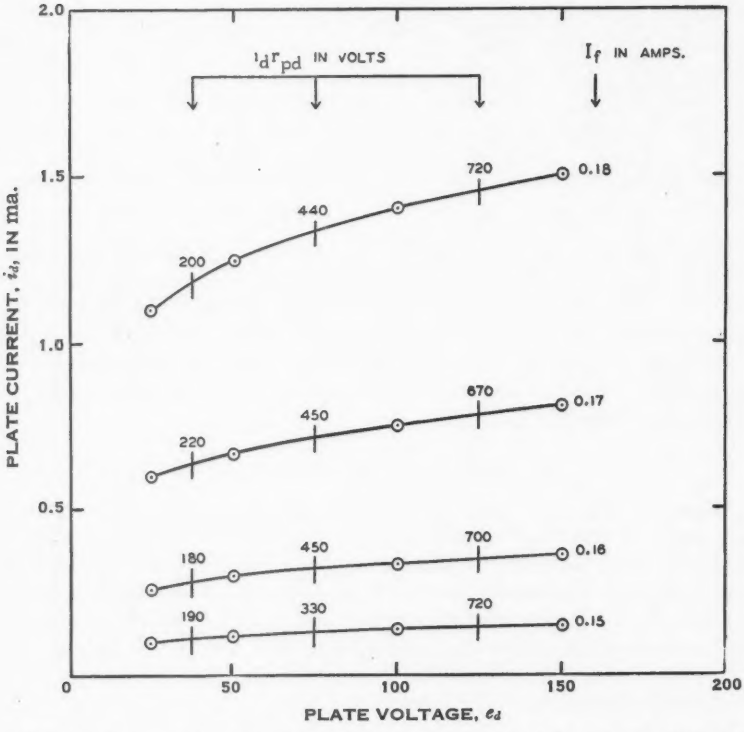

FIG. 2. *Pre-saturation plate characteristics of a type 01A triode used as a diode, with indications of the constancy of $i_d r_{pd}$ for constant plate voltage.*

TABLE I

PLATE RESISTANCE VALUES FOR VARIOUS OPERATING POINTS USING A TYPE 80 DOUBLE DIODE. BOTH PLATES CONNECTED

I_f : 1.0 to 1.2 amp.

e_d, volts	i_d, ma.	r_{pd}, megohms	$i_d r_{pd}$, volts
75	0.165	1.25	210
	1.00	0.250	250
	1.65	0.167	280
	5.50	0.050	275
125	0.195	1.67	325
	1.20	0.250	300
	1.95	0.167	325
	6.50	0.050	325

TABLE II

MEAN VALUES OF $i_d r_{pd}$ FOR CONSTANT PLATE VOLTAGE USING VARIOUS TUBES AS DIODES

Type	e_d = 75 v.			e_d = 125 v.		
	i_d, ma.	$i_d r_{pd}$, volts	Percentage deviation	i_d, ma.	$i_d r_{pd}$, volts	Percentage deviation
6H6	0.4 to 2.4	290	3			
1-V	0.2 to 1.2	110	6	0.1 to 1.7	210	5
80	0.2 to 5.5	270	5	0.2 to 6.5	320	1
X99	0.3 to 0.7	325	1	0.4 to 0.7	500	2
01A	0.3 to 1.3	445	1	0.1 to 1.4	700	1
27	0.2 to 0.8	295	1	0.2 to 0.9	465	3
6F5	0.3 to 0.7	200	2	0.4 to 0.8	295	1
6J7	0.4 to 1.7	270	2	0.5 to 1.9	420	4

$\log e = m \log i +$ a constant. That is, $e_d = Ci_d^m$ for constant cathode temperature. Thus, plotting $\log e_d$ against $\log i_d$ for constant cathode temperature should yield a straight line with slope m. Moreover, if m is independent of cathode temperature (as indicated above), the logarithmic characteristics for different cathode temperatures should be parallel.

Fig. 3 illustrates the logarithmic characteristics for the same data as employed in Fig. 2. It will be noted that although the characteristics are linear, they are not exactly parallel. The slope, m, is however reasonably constant for $i_d < 2.0$ ma. corresponding to $I_f < 0.19$ amp.

According to the Schottky equation (2, 3) the saturation current is dependent on both temperature and field strength and is expressed by the relation $I = I_0 \, exp \, sV^{\frac{1}{2}}/T$, with I_0 a function of temperature alone. This yields $i_d r_{pd} = (2T/s)V^{\frac{1}{2}}$, which is not in agreement with the observed values of K. It is interesting to note that Becker and Mueller (1) and Reynolds (6), working with thoriated filaments, obtained a marked departure from the Schottky curve for field strengths less than 10,000 volts per cm.

C. The Pre-Saturation Diode as a Load Resistance

1. *Virtual Supply Voltage*

The use of the diode as a load resistance can now be considered, taking into account the relation $i_d r_{pd} = K$. Recalling Section $A2$, $e_b + e_d = E_{bb}$; hence for $R \gg r_{pd}$ the "load line" for the control tube is the reversed anode characteristic of the diode. This is shown as the curve ABN in Fig. 4. Also $i_b = i_d$, whence $i_b r_{pd} = K$.

Consider Fig. 4 with $E_{bb} = 200$ v., $E_{bo} = 75$ v., and $I_{bo} = 1.0$ ma. to yield the operating point Q. Then small variations in grid voltage will yield transient points on AB. Let AB produced cut the voltage axis at the point C (voltage V_c). Then the slope of AB equals $-\frac{QM}{MC} = \frac{-I_{bo}}{V_c - E_{bo}}$. But the slope of AB is also expressed by $-1/r_{pd}$, whence $V_c - E_{bo} = I_{bo} r_{pd}$.

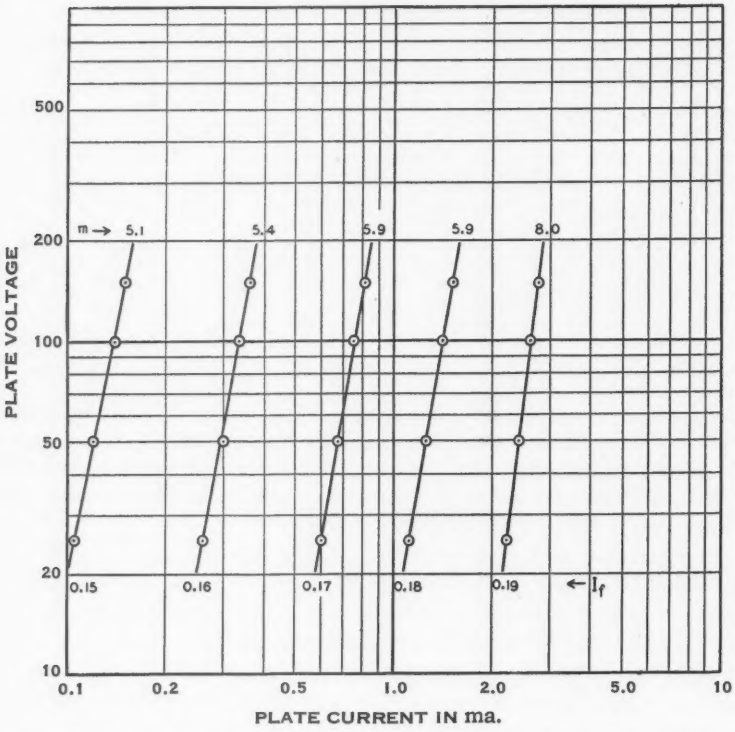

FIG. 3. *Logarithmic plate characteristics of a pre-saturation diode. Type 01A triode used as a diode.*

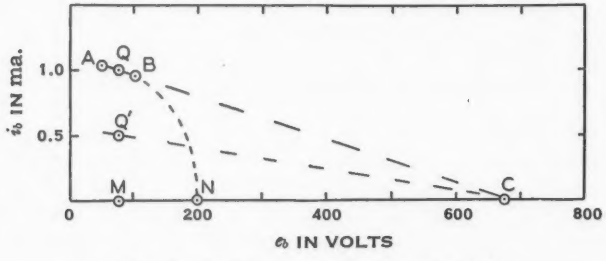

FIG. 4. *Load lines for a pre-saturation diode.*

However, it has been shown that for constant plate voltage $i_b r_{pd} = K$. If then in practice we are concerned with only small variations in e_b about a given quiescent value E_{bo}, V_c will be independent of the value of I_{bo} since $V_c = E_{bo} + K$. Accordingly, we can consider all load lines as converging at the point C. Thus V_c is the supply voltage that would be required to

give the same operating point when using a fixed resistance of value r_{pd}. Therefore V_c might be called the virtual supply voltage, E'_{bb}.

In order to compare E'_{bb} with E_{bb}, assume $E_{bo} = \frac{1}{2}E_{bb}$, whence $E'_{bb} = \frac{1}{2}E_{bb} + K$. Table III provides a comparison for different supply voltages. It is to be noted that the value of K that is applicable is dependent on E_{bo}.

TABLE III

COMPARISON OF REAL AND VIRTUAL SUPPLY VOLTAGES USING A TYPE 01A TUBE AS A DIODE

E_{bb} = 150 v.	E_{bb} = 250 v.
K = 450 v.	K = 700 v.
E'_{bb} = 525 v.	E'_{bb} = 825 v.

2. *The Dependence of Voltage Gain on the Operating Point*

Since the voltage gain $G = \mu/(1 + r_p/r_{pd})$ then for maximum gain one is inclined to make r_{pd} as large as possible, i.e., to have I_{bo} as small as possible. It should be noted however that this does not necessarily result in an increase in voltage gain, since r_p is also dependent on I_{bo}. Tube manuals usually give the r_p of a pentode for one set of operating conditions and indicate that if the voltage is increased or the current decreased, the value of r_p is greater than 1 megohm. In order to have more definite information regarding r_p for small values of i_b, measurements were made on a 6J7 tube. The data for several plate voltages are given in Table IV.

TABLE IV

PLATE RESISTANCE VALUES FOR A 6J7 TUBE

Screen volts = 100, E_f = 6.3 v.

e_{b_1} volts	i_{b_1} ma.	r_{p_1} megohms	$i_b r_{p_1}$ volts
35	1.89	0.47	890
	1.42	0.63	890
	0.89	0.83	740
	0.55	1.25	690
	0.27	2.50	670
75	1.95	1.00	2000
	1.45	1.70	2500
	0.91	2.50	2300
	0.57	5.00	2800
	0.27	10.0	2700
125	1.98	1.7	3400
	1.48	2.0	3000
	0.93	3.3	3100
	0.58	5.0	2900
	0.28	10.0	2800

It will be noticed that in spite of very large changes in i_b, the product $i_b r_p$ is fairly constant for constant plate voltage. Thus the ratio r_p/r_{pd} should be reasonably independent of plate current for E_{bo} constant. This makes the voltage gain dependent only on μ.

When $E_{bo} = \frac{1}{2}E_{bb}$ the operating voltage for the pentode is the same as that for the diode. Thus for $E_{bb} = 150$ v. using a 6J7 with an 01A as a diode $r_p/r_{pd} = 2600/450 = 6$, which yields $G = \mu/7$. However, greater gain can be obtained by shifting the operating point to have $E_{bo} < \frac{1}{2}E_{bb}$ with a consequent decrease in r_p and an increase in r_{pd}. This can be effected by changing either the grid bias for the pentode or the filament current of the diode. The data for Fig. 5 were obtained by keeping the filament current

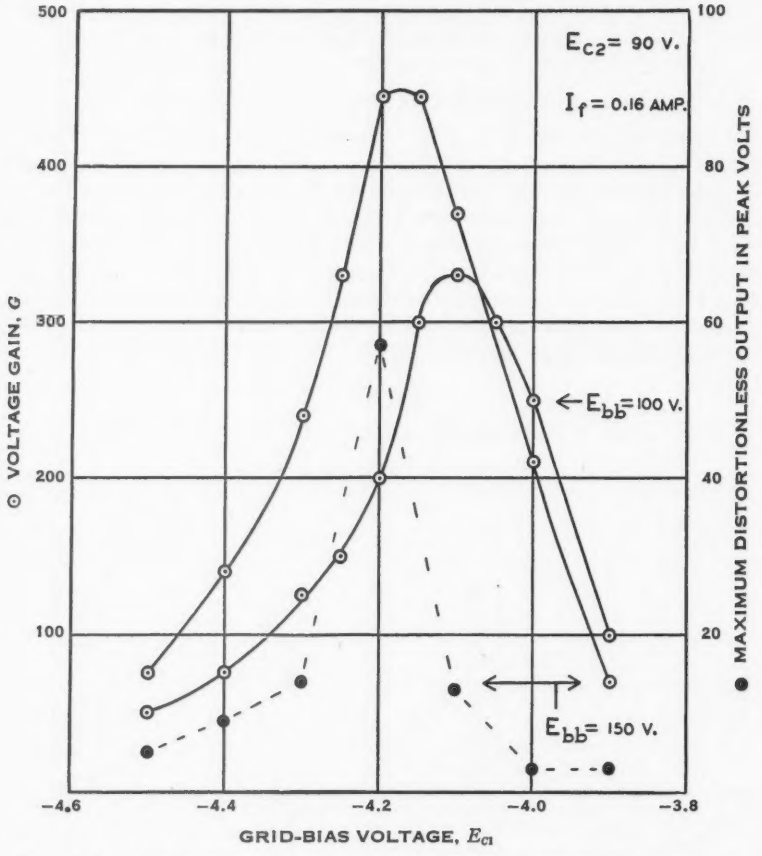

FIG. 5. *The effect of grid-bias on voltage gain and on maximum distortionless output, using a 6J7 with an 01A as a pre-saturation diode. E_g, 100 c.p.s. adjusted for maximum distortionless output.*

constant and for each grid bias, E_{c1}, adjusting the input signal, E_g, for maximum distortionless output. All output voltages were measured and examined by means of a cathode ray oscilloscope. Fig. 5 shows how the voltage gain can be made greater than $\mu/7$ and yet permit a large output voltage which is free of distortion. Fig. 5 shows also the effect of supply voltage on maximum gain.

With the diode operating on a fixed filament current, self-bias can be used on the pentode to secure the proper operating point. However, owing to the large amplification, a rather large capacitance is required in parallel with the self-bias resistor. Fig. 6 indicates that the self-bias resistor can be employed as a gain control that is not too critical for maximum gain.

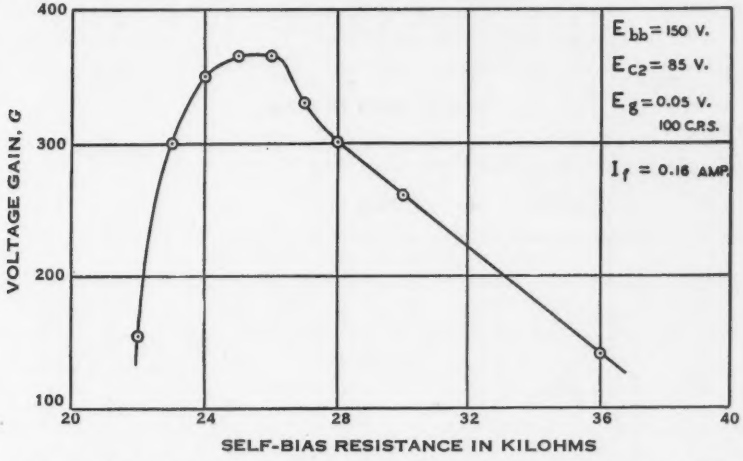

FIG. 6. *The effect of self-bias resistance on voltage gain, using a 6J7 with an 01A as a pre-saturation diode.*

3. *The Dependence of Voltage Gain on Frequency*

In using the diode as a load, it cannot always be treated as a pure resistance, because of the anode to cathode capacitance. Accordingly the gain is given by the expression $G = \mu Z_L/(r_p + Z_L)$, with Z_L dependent on frequency. Fig. 7 shows how the gain varies with frequency, being almost constant for frequencies less than 300 c.p.s. but decreasing rapidly for higher frequencies. Output voltages were measured by means of a cathode ray oscilloscope.

4. *Comparison of Pre-Saturation Diode and Fixed Resistance*

Table V provides a comparison of the results obtained by the use of a diode and of a fixed resistance as load, both being adjusted to yield maximum gain for a given grid bias. It will be noted that for both voltage gain and maximum distortionless output the diode is superior to the fixed resistance. The advantages of the diode when used with a small supply voltage are particularly noteworthy.

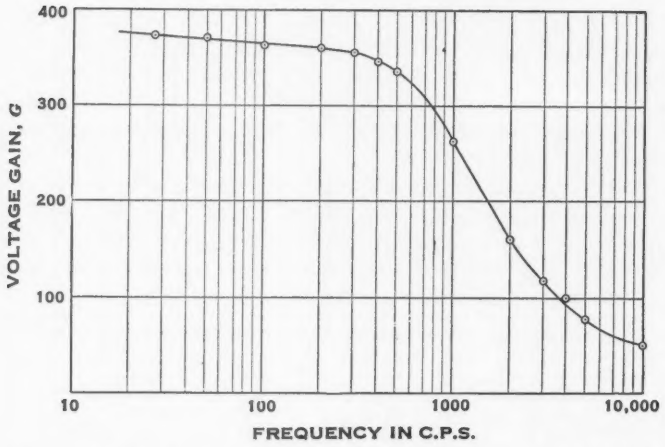

FIG. 7. *The effect of frequency on voltage gain, using a 6J7 with an 01A as a pre-saturation diode.* $E_{bb} = 150$ *v.*; $E_{c2} = 85$ *v.*; $E_{c1} = -4.2$ *v.*; $E_g = 0.10$ *v.*; $I_f = 0.16$ *amp.*

TABLE V

PRE-SATURATION DIODE VERSUS FIXED RESISTANCE, R_L, AS LOAD USING A 6J7 WITH AN 01A AS A DIODE

$E_{c1} = -4.2$ v.		$E_{c2} = 85$ v.		$I_{bo} = 0.25$ ma.	
E_{bb} volts	R_L megohms	Voltage gain		Maximum distortionless output in peak volts	
		R_L	Diode	R_L	Diode
100	0.25	115	300	10	35
150	0.25	180	430	30	50

Although tests have been conducted using the pentode and the diode as separate tubes, it is apparent that both pentode and diode could be included in the same envelope.

References

1. BECKER, J. and MUELLER, D. Phys. Rev. 31 : 431-440. 1928.
2. COMPTON, K. T. and LANGMUIR, I. Rev. Modern Phys. 2 : 123-242. 1930.
3. DUSHMAN, S. Rev. Modern Phys. 2 : 381-476. 1930.
4. HERD, J. F. Exptl. Wireless and Wireless Eng. 8 : 192-195. 1931.
5. MILLS, J. U.S. Pat. 1,548,952. 1921.
6. REYNOLDS, N. B. Phys. Rev. 35 : 158-171. 1930.
7. RUDOLPH, H. Arch. Elektrotech. 24 : 1-3. 1930.

CANADIAN JOURNAL OF RESEARCH

Notes on the Preparation of Copy

General:—Manuscripts should be typewritten, double spaced, and the **original and at least one extra copy** submitted. Style, arrangement, spelling, and abbreviations should conform to the usage of this Journal. Names of all simple compounds, rather than their formulae, should be used in the text. Greek letters or unusual signs should be written plainly or explained by marginal notes. Superscripts and subscripts must be legible and carefully placed. Manuscripts should be carefully checked before being submitted, to reduce the need for changes after the type has been set. **All pages, whether text, figures, or tables, should be numbered.**

Abstract:—**An abstract of not more than about 200 words, indicating the scope of the work and the principal findings, is required.**

Illustrations

(i) *Line Drawings:*—Drawings should be carefully made with India ink on white drawing paper, blue tracing linen, or co-ordinate paper ruled in **blue** only. Paper ruled in green, yellow, or red should not be used. The principal co-ordinate lines should be ruled in India ink and all lines should be of sufficient thickness to reproduce well. Lettering and numerals should be of such size that they will not be less than one millimetre in height when reproduced in a cut three inches wide. If means for neat lettering are not available, lettering should be indicated in pencil only. All experimental points should be carefully drawn with instruments. Illustrations need not be more than two or three times the size of the desired reproduction, but the ratio of height to width should conform with that of the type page. **The original drawings and one set of small but clear photographic copies are to be submitted.**

(ii) *Photographs:*—Prints should be made on glossy paper, with strong contrasts; they should be trimmed to remove all extraneous material so that essential features only are shown. Photographs should be submitted **in duplicate;** if they are to be reproduced in groups, one set should be so arranged and mounted on cardboard with rubber cement; the duplicate set should be unmounted.

(iii) *General:*—**The author's name, title of paper, and figure number should be written on the back of each illustration.** Captions should not be written on the illustrations, but typed on a separate page of the manuscript. All figures (including each figure of the plates) should be numbered consecutively from 1 up (arabic numerals). **Reference to each figure should be made in the text.**

Tables:—Titles should be given for all tables, which should be numbered in Roman numerals. Column heads should be brief and textual matter in tables confined to a minimum. **Reference to each table should be made in the text.**

References should be listed alphabetically by authors' names, numbered in that order, and placed at the end of the paper. The form of literature citation should be that used in this Journal and titles of papers should not be given. All citations should be checked with the original articles. Each citation should be referred to in the text by means of the key number.

The *Canadian Journal of Research* conforms in general with the practice outlined in the *Canadian Government Editorial Style Manual*, published by the Department of Public Printing and Stationery, Ottawa.

Reprints

Fifty reprints of each paper are supplied free. Additional reprints, if required, will be supplied according to a prescribed schedule of charges.